X-900-75-216
PREPRINT

NASA TM X- 70959

SEA SURFACE DETERMINATION FROM SPACE

THE GSFC GEOID

(NASA-TM-X-70959) SEA SURFACE DETERMINATION FROM SPACE: THE GSFC GEOID (NASA) 14 p HC $3.25 CSCL 08J
N75-30758
Unclas
G3/48 34738

F. O. VONBUN
J. McGOOGAN
J. MARSH
F. LERCH

AUGUST 1975

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

X-900-75-216
Preprint

SEA SURFACE DETERMINATION

FROM SPACE

THE GSFC GEOID

F. O. Vonbun*
J. McGoogan**
J. Marsh*
F. Lerch*

August 1975

*NASA/GSFC
**NASA/Wallops

Presented at the 1974 USNC/URSI-IEEE Meeting, Boulder, Colorado
October 14-17, 1974

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

SEA SURFACE DETERMINATION FROM SPACE THE GSFC GEOID

F. O. Vonbun
J. McGoogan
J. Marsh
F. Lerch

ABSTRACT

This paper deals with a new area of radio oceanography, namely, with the determination of the sea surface/geoid and its relative variation. Results of the altimeter experiment on Skylab to test the Goddard Space Flight Center (GSFC) geoid are discussed. The spaceborne altimeter on Skylab revealed for the first time that the sea surface of the world's oceans can be "measured" with an accuracy in the meter range. Surface variations are discussed as they relate to those "computed" from satellite orbital dynamics and ground based gravity data obtained from the Defense Mapping Agency--Aerospace Center, and other organizations. The recent GSFC geoid has been constructed from about 400,000 satellite tracking data (range, range rate, angles) and about 20,000 ground gravity observations. One of the last experiments on Skylab was to measure and/or test this geoid over almost one orbit. It was found that the computed water surface deviates between 5 to 20 m from the measured one. Further outlined are the influence of orbital errors on the sea surface and numerical examples are given based upon real tracking data. Theoretical orbital error analyses cannot shine any new light on these problems because the error values involved are in the meter range and the reliability of theoretical error analyses diminishes at these rather small values. Orbital height error estimates have been computed for geodetic type satellites and are found to be in the order of 0.2 to 5 meters. Such errors are generally larger for the Skylab due to its relatively low orbit, large area, venting and the fact that only conventional Unified S-Band data (range and range rate) were available for orbit computations. However, for the single revolution used in the analyses, orbit error amounted to only a few meters. Furthermore, orbit errors tend to be long wavelength type errors (~2000 km and longer) thus short wavelength oceanographic features, i.e., seamounts, trenches are clearly visible in the Skylab altimeter data.

CONTENTS

ILLUSTRATIONS

I. INTRODUCTION

The geoid is the equipotential surface that a uniform and static ocean would conform to under the influence of only the Earth's (atmosphere included) gravitational and rotational forces, excluding all other external forces (e.g. luni-solar and planetary gravitation, currents, and circulations, wind stresses, atmospheric pressure changes, and variations in density, temperature and salinity.) The real sea surface deviates from the geoid due to variations in sea water temperature and density (salinity) together with Coriolis forces acting on moving water masses and other forces. These "deviations" have been referred to as the "sea surface topography" [Mather, 1973] and can reach values of up to 2 meters or more. For example, a study by Stommel [1965] indicates the possible existence of a quasi-stationary variation of the sea surface of up to 1 1/2 m between the latitudes of $\pm 65^\circ$. Also, there is a rise of about 1 1/2 m in the water surface over 70 to 100 km due to the Gulf Stream to quote another example.

Sea surface variations of this magnitude will be detectable in the future assuming a further improvement to commensurate accuracies of the geoid, the earth's gravity field and our orbit determination capability. It is clear that satellite altimetry, if accurate to about 2 to 10 cm can significantly contribute to an explanation of the discrepancies which exist, for instance, between equipotential surfaces of the Earth's gravity field as obtained from geodetic leveling and the determination of the mean sea level using tide gauges. At the present time there is controversy on whether the discrepancies between measurements of equipotential surfaces obtained from geodetic leveling and mean sea level are real or not. Systematic errors (e.g., consistent sunshine from the equatorial regions biasing leveling, or variations from currents) could account for the discrepancies [Apel, 1975, personal communication]. Satellite altimetry also provides an independent means of decoupling the non-tidal gravitational forces from the others acting on the ocean surface [Mather, 1973].

In addition, a complete new set of precision satellite tracking data will be obtained in the form of height measurements by an altimeter spacecraft. This means a ten to thirty fold increase in the number of tracking observations, which will improve considerably our knowledge of the Earth's gravity field. In principle, there is no difference between ranging data obtained from a ground based tracking system and that from an altimeter. Such experiments were first conducted during the SKYLAB mission in 1973-1974.

NASA launched an altimeter equipped spacecraft, namely, GEOS-C (now GEOS-3) [Vonbun, 1971] in April 1975 and more sophisticated oceanographic spacecraft, namely, SEASAT-A is planned for a 1978 launch. These latter two spacecraft are part of NASA's Earth and Ocean Physics Program - EOPAP

[NASA, 1971; Vonbun, 1972]. A major part of this effort will be directed to the study of the sea surface topography as well as the surface wind fields and ocean waves, their direction and height.

II. THE "MEASURED" SEA SURFACE

The last Skylab mission, SL-4 flown from November 1973 until early February 1974, gave a real opportunity to "measure" or partially test the GSFC GEM-6 Detailed Geoid (ocean surface) over part of one orbit. Previous to this, geoid comparisons were performed only among different models (Goddard Space Flight Center, Smithsonian Astrophysical Observatory and Ohio State University). Height variations between the different geoidal models as large as 20 m were observed together with longitudinal and latitudinal shifts of 500 to 1000 km of certain long wavelength features. As will be explained later, orbital error problems as well as the overall system accuracy do not permit the detection of ocean surface variations in the one meter region at this time. However, this first altimeter data is quite valuable in that it provides the first independent data for comparisons with geoids in ocean areas derived with surface and satellite gravity data.

A. THE GODDARD SPACE FLIGHT CENTER GEOID

During the past few years, a rather extensive effort was undertaken at Goddard to improve the knowledge of the Earth's gravitational field. At present there exist six gravitational field models at GSFC. These are designated as Goddard Earth Models GEM 1 through GEM 6. The odd numbers designate gravity fields purely derived from spacecraft tracking data (Optical, Doppler, Radar, Range and Range Rate, Lasers) and the even numbered ones are based upon a combination of satellite tracking data and ground based gravity measurements. Of specific interest for this discussion is the recent Goddard Earth Model GEM-6 [Lerch, et al., 1974] which is based upon a combination of about 400,000 precision tracking data of 27 satellites and 1654 5° equal area mean gravity anomalies. This model is complete to degree and order 16 with some additional terms up to degree 22. Marsh and Vincent [1974] have developed a model of a rather detailed gravimetric geoid using this GEM-6 gravity field as a base (Figure 1). They have computed a detailed gravimetric geoid by combining the GEM-6 with surface gravity data. About 24,000 1° x 1° mean free air gravity anomaly values obtained from the Defense Mapping Agency/Aerospace Center were used in the computation. This gravity collection was further augmented with data from the National Oceanic and Atmospheric Administration (NOAA) and many other sources. The accuracy of this geoid (approximately the mean sea surface) is on the order of 3 to 5 meters over most of the northern ocean areas and 20 to 15 meters in areas of the

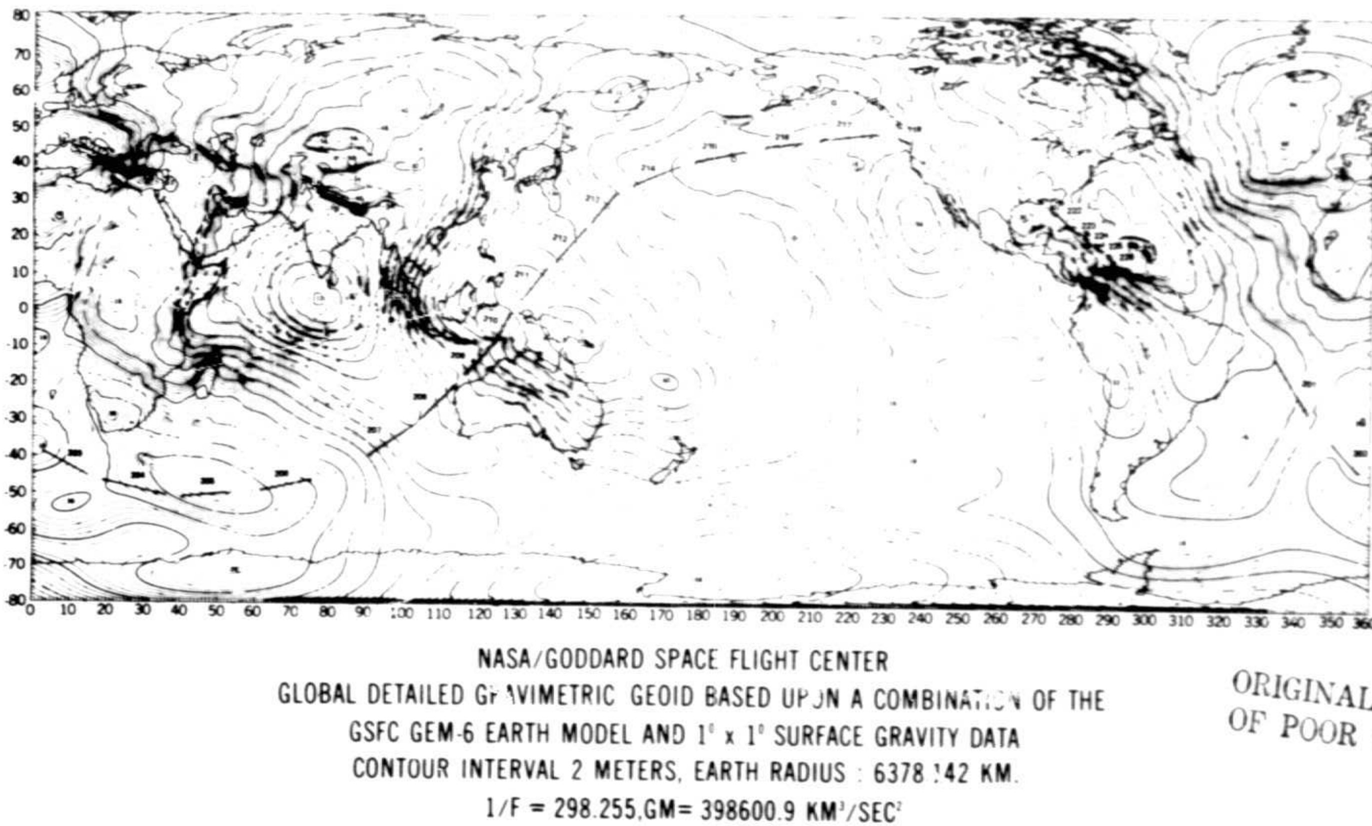

Figure 1. Skylab IV Altimeter "Round-the-World Data Take" January 31, 1974

southern hemisphere where usually no surface gravity data are available [Marsh and Vincent, 1974].

B. THE SKYLAB "TEST" OF THE GEOID

In the past, there was really no economic way to test a global geoid via metric measurements. Skylab, carrying for the first time an orbiting active radar altimeter, made such an experiment possible. Toward the end of Skylab IV the astronauts turned on the radar altimeter over almost a full orbit as shown in Figure 1. Figure 2 depicts both the computed sea

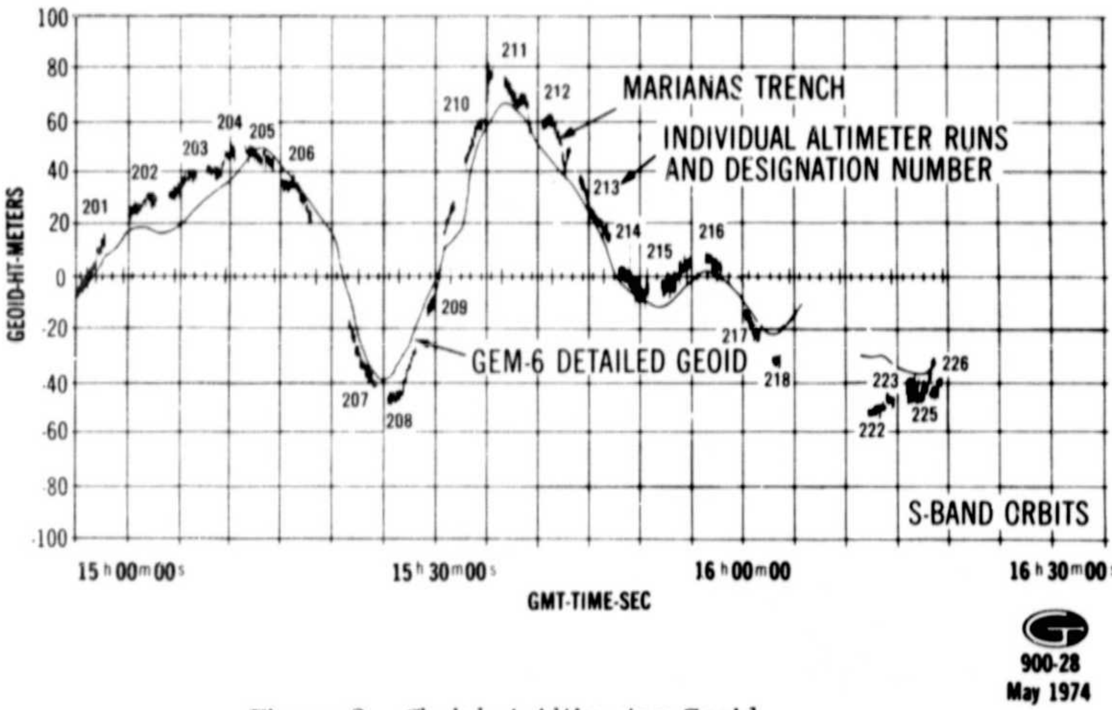

Figure 2. Skylab 4 Altimeter Geoid

surface and the measured one. The computed sea surface refers to the departures of the gravimetric geoid from a reference ellipsoid (ae = 6378142 m, 1/f = 298.25). The r.m.s. deviation between the computed and measured sea surface is 8 m. These differences reflect the effects of three main error sources: 1) orbit errors; 2) errors in the gravimetric geoid; and 3) errors in the altimeter system. Orbit determination for SKYLAB is certainly not the easiest one to perform to a high degree of accuracy. Relatively large drag and maneuvering (control rocket firing) make a precision determination of the orbit impossible as compared to other more "geodetic" type spacecraft [Vonbun, 1970]. Orbit errors are estimated to be in the meter range for this particular case, due to the intensive tracking by the Unified S-Band System and the fact that the arc length was restricted to a single revolution. Thus, the differences are primarily due to the latter two error sources. The good agreement shown in Figure 2 is significant proof of the value of a radar altimeter for sea surface determination.

A closer examination shows that radar runs 202 and 203 deviate as much as 10 to 15 m from the computed geoid or sea surface in this case. This rather large deviation is primarily attributed to error in the gravimetric geoid in this area. Unless one considers deviations smaller than 1.5 to 2 m one does not need to make specific reference to the sea surface topography as mentioned earlier. Further tidal effects and atmospheric conditions are not taken into account for the same reason. These factors will however play an important role in the future when overall accuracies will reach the one meter level. It should be borne in mind that this is the first test of satellite altimetry.

Even though Figure 2 shows the overall picture, some details seem to be significant. For instance, the Marianas Trench is clearly visible on altimeter run #212 even on this global scale.

C. TRENCHES AND SEAMOUNTS

Looking somewhat closer, one can distinguish such features as ocean trenches and seamounts as was shown by McGoogan [1974]. Figure 3 depicts the Puerto Rican Trench and Figure 4, the Marianas Trench (#212) in a very clear fashion. Note that the Goddard geoid does not follow these short wave length features. This was never anticipated since the smallest wavelength of the GEM-6 model is in the order of 2500 km or approximately 22 1/2 degrees on the earth surface. As can be seen, the altimeter geoid is about 30 m displaced from the GEM-6 geoid. This is due to a combination of orbital height errors, long wavelength errors in the GEM-6 geoid and errors in the altimeter system and has nothing to do with the trench determination itself. As a matter of fact, this demonstrates quite clearly that orbital altimetry is a very powerful tool for studying details of the sea surface variations independent of the orbital constraints and/or errors.

This holds at least over distances of, say, 200 to 400 km. It can safely be assumed that the spacecraft orbit will not follow such sudden changes as these features would require, due to the "attenuation" of the gravity field errors at spacecraft altitudes. Figure 5 shows the opposite, namely, a seamount at the Cape Verde Islands. A detailed analysis of the altimeter footprint noise characteristics and ground track indicated that the altimeter was not over land during this particular pass. Therefore, the "water hill" shown in the altitude measurement at $15^h 41^m 30^s$ is not due to a partial sensing of one of the Cape Verde Islands. These short wavelength oceanographic features (hills and valleys) which are clearly observable in Figures 3, 4, and 5 are above the radar noise and are a direct result of the deflections of the local gravity vector. These deflections are

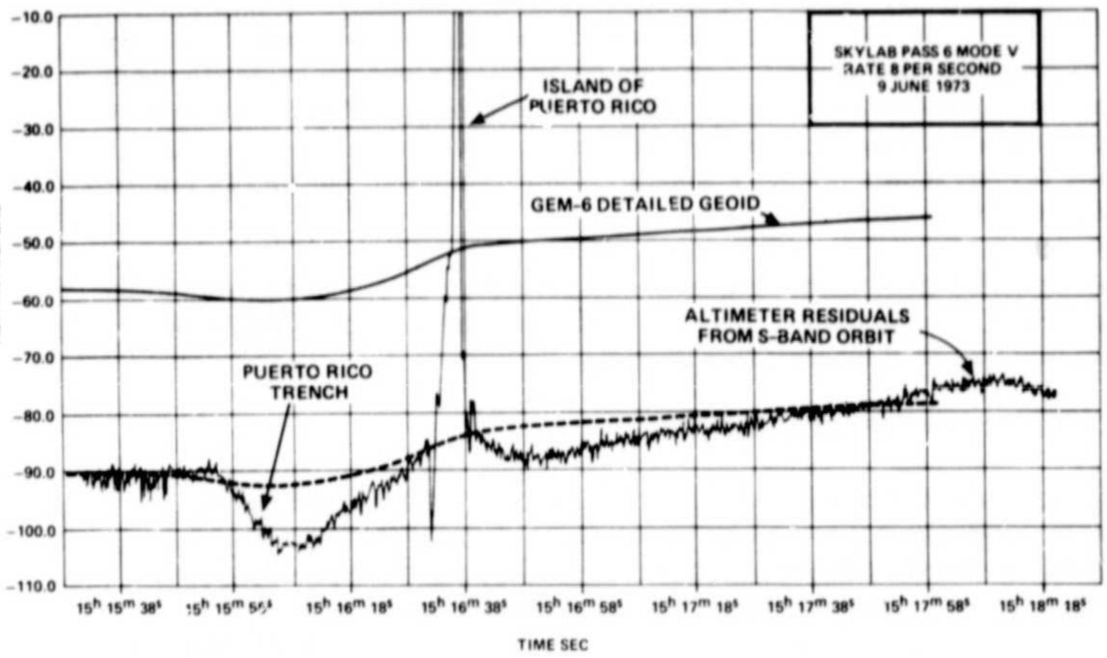

Figure 3. Skylab Altimeter Measurements

caused both by mass variations (shape of the bottom topography, i.e., subsurface mountain ranges and trenches) and by density variations within the Earth. With the radar height noise of approximately one meter one certainly can expect to distinguish even much smaller features than those shown in these graphs. It is anticipated that many more interesting features of the ocean surface will be discovered from GEOS-3 data.

III. ORBITAL ERRORS AND SEA SURFACE TOPOGRAPHY

As mentioned briefly before, if altimetry is to be expected to operate very accurately (dm-range or better) on a global basis, the orbit of the altimeter

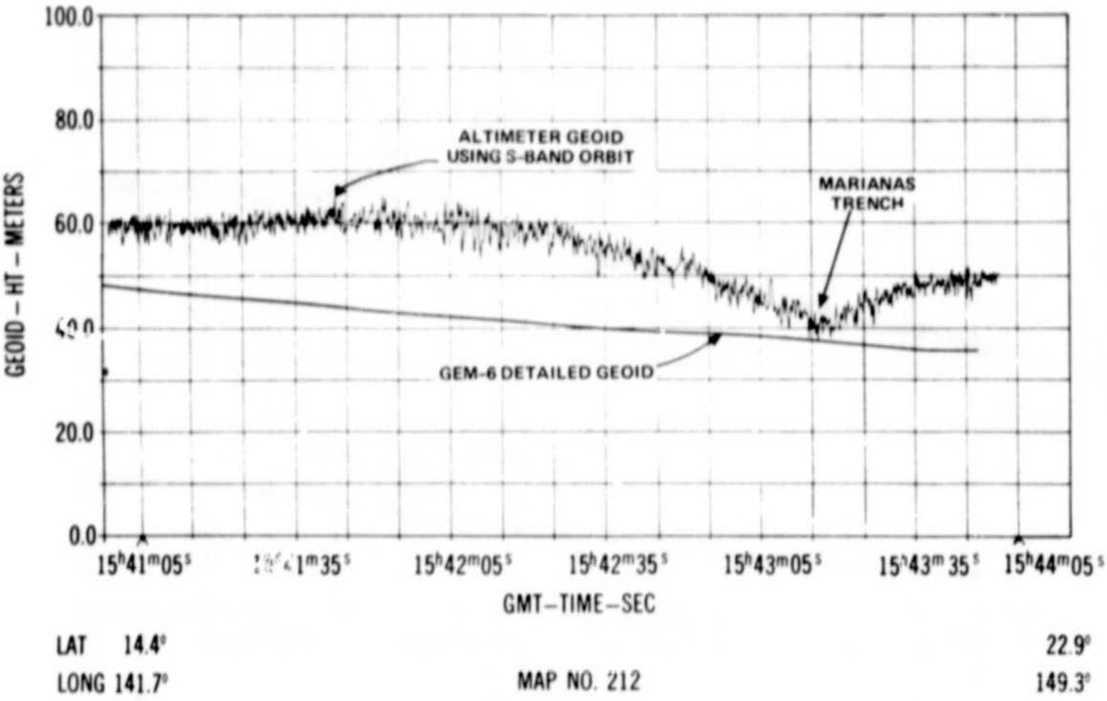

Figure 4. Skylab IV Pass 97 Mode 1, 31 Jan. 1974

spacecraft has to be known to within an equivalent error. Additional conditions such as requiring the water masses of the total oceans to be constant over one or two days may be necessary so that the sea surface topography can be more accurately determined than the orbital height. A gain of a factor of 3 to 4 may be possible according to Mather [1975]. This could mean that a sea surface topography error of say 10 cm could be achieved even though the height of the spacecraft may not be known to 30 to 40 cm. If this can be accomplished it would certainly be of great help but we should, at the moment, assume a one-to-one relationship only to be conservative. Thus, the errors in the orbit have to be reduced considerably if the sea surface topography error goal of 2 to 10 cm is to be obtained in the future.

Where do we stand at this time as far as orbital uncertainties are concerned? Error studies are certainly important and are being used in our investigation but extreme caution should be exercised in their interpretation since it is very difficult to compare "computed" errors with real ones [Vonbun, 1970]. For the consideration at hand we used actual tracking data and our best orbit computation model. Figure 6 shows orbital uncertainties obtained for GEOS-2

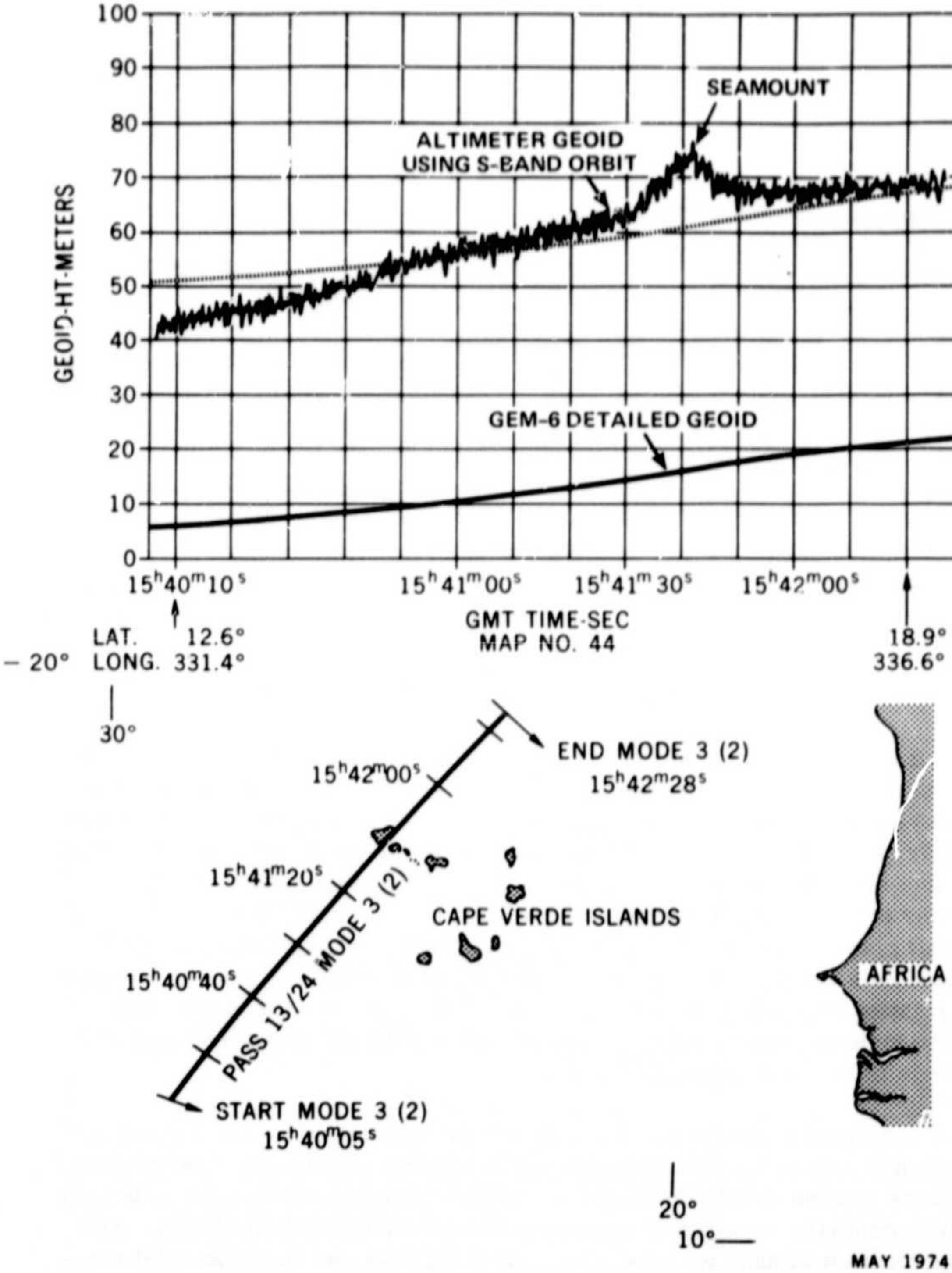

Figure 5. Skylab III, Pass 13 Mode 3, 3 Sept. 1973

- **NWL-DOPPLER DATA:** ~1000 OBSERVATIONS

GRAVITY FIELD	MAY 23, 1968 RADIAL	MAY 23, 1968 CROSS TRACK	MAY 23, 1968 ALONG TRACK	MAY 24, 1968 RADIAL	MAY 24, 1968 CROSS TRACK	MAY 24, 1968 ALONG TRACK
GEM-1	0.8	2.1	3.2	0.4	0.8	8.5
GEM-6	1.2	1.6	7.0	1.1	0.2	3.3
SAO-2	4.8	16.7	21.2	6.8	10.8	16.0

- **OPTICAL DATA:** 330 OBSERVATIONS

GRAVITY FIELD	MAY 23, 1968 RADIAL	MAY 23, 1968 CROSS TRACK	MAY 23, 1968 ALONG TRACK	MAY 24, 1968 RADIAL	MAY 24, 1968 CROSS TRACK	MAY 24, 1968 ALONG TRACK
GEM-1	0.2	2.4	4.0	3.1	5.6	6.5
GEM-6	1.9	3.2	5.1	3.8	2.3	10.7
SAO-2	2.7	13.5	16.2	7.9	7.6	24.0

900 - 33
May 1974

Figure 6. Satellite Orbital Uncertainty Estimates (OUE) or Overlap Differences in Meters for GEOS-II

using both doppler and optical tracking data with different earth gravity fields. Using the "overlap method" [Siry and Stewart, 1969; Vonbun, 1970] height uncertainties between 0.2 to 4.8 meters have actually been obtained. These values give an indication of the orbital height uncertainties one can expect at present when a two day rather stable orbital arc is computed using our best numerical orbit computation system and Earth models at GSFC.

IV. CONCLUSIONS

In conclusion, it can be stated that: a) it was possible to measure the sea surface variations (geoid) along a major part of an orbit; b) the deviations of the computed and measured geoid agree quite well for this first test; c) details such as trenches and seamounts can easily be identified independent of the orbit errors; d) the orbital height errors for geodetic type spacecraft at present are of the order of meters; e) these errors will considerably be reduced in the next few years, particularly after GEOS-3 data are fully analyzed and thus our present knowledge of the earth's gravity field is improved; and, therefore, f) future altimeter spacecraft such as SEASAT-A should be able to determine variations of the sea surface of the order of dm.

ACKNOWLEDGEMENT

The authors acknowledge the very helpful written comments of Dr. John Apel on this paper.

REFERENCES

Lerch, F. J., C. A. Wagner, J. A. Richardson and J. E. Brownd (1974), Goddard Earth Models (5 and 6), GSFC Report X-921-74-145, GSFC Contribution to NGSP Final Report (may be obtained from the Technical Information Division, Code 250, Goddard Space Flight Center, Greenbelt, Maryland 20771).

Marsh, J. G. and S. F. Vincent (1974), Global Detailed Geoid Computation and Model Analysis, Geophysical Surveys (1), 482-511.

Mather, R. S. (1975), On the Evaluation of Stationary Sea Surface Topography Using Geodetic Techniques, Bulletin Geodesique, No. 115, 65-81.

McGoogan, J. T. (1974), Precision Satellite Altimetry, 1974 IEEE Intercon Technical Papers, Session 34.

McGoogan, J. T., L. S. Miller, G. S. Brown, and G. S. Hayne (1974), The S-193 Radar Altimeter Experiment, Proceedings of IEEE, Volume 62, No. 6.

NASA-1970 (W. Kaula, Chairman) (1970), The Terrestial Environment: Solid-Earth and Ocean Physics, Williamstown Report.

Stommel, W. (1965), The Gulf Stream, University of California Press, Berkeley, California.

Siry, J. W. and D. J. Stewart, (1969), Goddard Orbit Information, GSFC Report X550-69-136 (may be obtained from the Technical Information Division, Code 250, Goddard Space Flight Center, Greenbelt, Maryland 20771).

Vonbun, F. O. (1970), Satellite Trajectory Determination and Their Expected Errors, OGO-IV, GEOS-I, Dynamics of Satellites, Springer Verlag, Berlin, Germany.

Vonbun, F. O. (1971), Geodetic Satellite Mission and GEOS-C Spacecraft, Space Research XI, Academic-Verlag, Berlin, Germany.

Vonbun, F. O. (1972), Earth and Ocean Physics Program (EOPAP), Astronautical Research, D. Reidel Publishing Company, Dordrecht, Holland, 239-245.